Electric vehicles and demand response: an economic perspective

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ABSTRACT

This paper presents a preliminary economic study on the feasibility of using electric vehicles (EVs) to provide demand response, carried out as part of the GREEN Grid project. A mathematical model is developed to track the charge cycle of an EV battery, and this in turn provides estimates of the cost associated with battery life degradation under different scenarios. Three case studies are presented in this paper: the first investigates the potential cost saving for the EV owner by confining the charging of an EV battery to the night tariff period; the second investigates the financial gain associated with regulating the charging of an EV battery based on spot prices; and the third investigates the possible economic benefit for the EV owner of participating in the electricity market by buying energy at low prices and selling at high prices. The first case also includes the situation of just a battery being used to store energy during the night to run a household during the day.

Results show that it is most economical to charge an EV during the night (Case 1), but that it varies considerably depending on the region in New Zealand. Regulating the charging rate depending on the spot price (Case 2) provides a small benefit. Using the EV to trade energy (Case 3) is, in most cases, uneconomic given the degradation of battery life. The variation of Case 1 also shows that at current battery costs, it is not economic to store energy during the night for use during the day. Given that there will be other costs associated with these activities, such as the charger equipment capable of both importing and exporting energy from the grid, the economics do not appear to favour use of EVs for demand response provision, except for the case of simply adjusting the time of charging to suit the tariff.

1. INTRODUCTION

As the uptake of electric vehicles (EVs) increases across the globe, regional policy makers and power system planners have been investigating the possible adverse effects as well as the possible benefits of having EV fleets connected to power grids. Conventionally, plug-in electric vehicles (PEVs) or plug-in hybrid electric vehicles (PHEVs) can be classified as dynamic loads for the power system as they consume energy from the grid to recharge the batteries from time to time. This has led to the development of smart charging concepts for controlled unidirectional power flow based either on grid conditions or user preferences and it is sometimes referred to as V1G [1]. On the other hand, with bi-directional power flow converters, the energy stored in the batteries could be used to feed power back directly to the power system; this is often referred to as vehicle-to-grid (V2G).

The advantage of V1G includes minimising additional load at peak times or reducing the cost of charging whereas V2G enables the possibility for EV owners to provide grid stabilising ancillary services such as frequency keeping, or even sell energy back to the grid when it is economically viable. The first description of the key concepts of V2G was published by Kempton and Letendre in 1997 [2]. The analysis was primarily based on a scenario where the stored energy in the EV batteries are used to provide peaking power. They argued that the value of such scheme for the utilities outweighs the cost of battery life reduction, and the utilities could offer a vehicle purchase or maintenance subsidy as an incentive to the owners. Later in their subsequent research, they realised this V2G proposal was less beneficial than what they originally thought.

In 2000, Kempton and Kubo presented an analysis of using V2G to provide peaking power in Japan [3]. In this work, they included the effect of the driving pattern in Japan and concluded that without a reduction in the cost of EV batteries or a change in the current rate structure, it is uneconomical for EV owners to sell energy from their batteries for peaking use. Later, in 2002, Letendre and Kempton extended on their previous work to include an economic assessment of other V2G applications, namely providing power for baseload, spinning reserves, and frequency regulation [4]. Figure 1 provides an illustration of the power flow and the state of charge (SOC) for an EV battery that is used for frequency regulation ancillary service. The EV is assumed to be plugged in at both home and work except when it is used for commute at 8 am and 6 pm, this can be seen from the large positive power output at these times while the negative spikes are due to regenerative braking during the commute. The net transfer of energy in the battery is small because this V2G application is assumed to be providing both up and down regulation, except after each commute i.e. the regulation is controlled to provide a net charge. They concluded that due to the high per kilowatt-hour (kWh) cost, V2G cannot be used for baseload application. However, there is economic value for V2G to provide ancillary services in California such as spinning reserve and regulation according to their study. The benefit is enough to offset the high initial cost of EVs. However, this requires design modifications to the current EVs as well as a review of current policies.

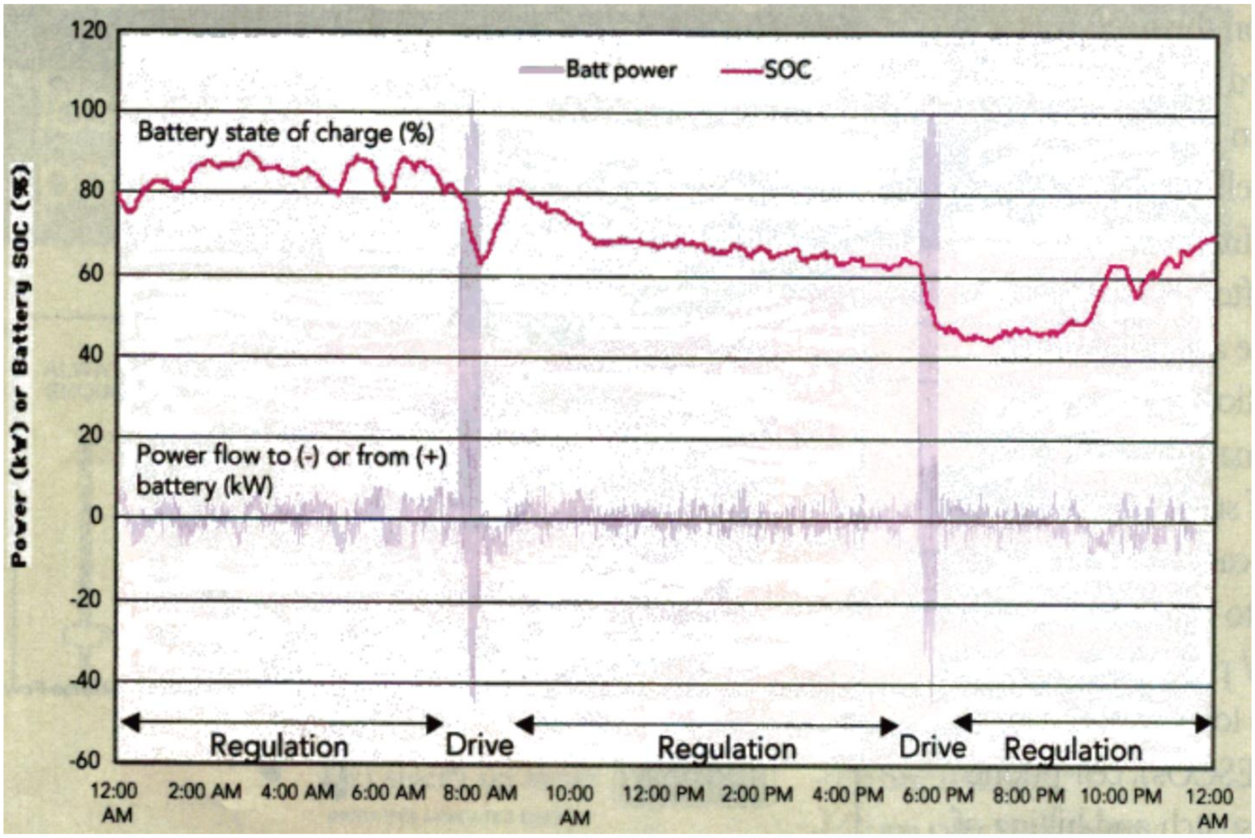

Figure 1: The power output and battery state of charge for an electric vehicle providing frequency regulation ancillary service [4].

In 2005, Kempton and Tomić presented similar research on three different types of electric vehicles - battery EV, fuel cell EV, and hybrid EV for V2G applications [5]. Their conclusion was that V2G is economically beneficial when there is a capacity payment i.e. a payment for having the EV batteries online and available for dispatch, with an additional energy payment for when power is actually dispatched. This is often the case for participating in the ancillary service market in the US. In such environment, V2G can make a profit from the capacity payment even if it is losing money for energy dispatched at low prices.

More recently in 2014, Parsons et al. presented their research on consumer willingness to pay for vehicle-to-grid electric vehicles and their contract terms [6]. They conducted a national survey in the US with more than three thousand respondents and found that drivers do not like fixed requirements such as minimum monthly plug-in time even if the target can be easily achieved. The results indicate that drivers prefer a more flexible arrangement such as a variable payment scheme where the payment depends on the amount of time the EVs stay connected to the grid.

In 2009, Peterson et al. presented a paper on the economics of using plug-in hybrid EV batteries for electricity arbitrage in the cities of Boston, Rochester, and Philadelphia [8]. These three cities were chosen because of their annual mean temperatures were not likely to have an impact on the modelled battery state of charge. They assumed that the batteries were charged when power cost was low and discharged back into the grid when the power cost was high. They also assumed that the batteries were fully charged every morning ready for the daily commute. The results show that with the cost of battery degradation due to the extra charging cycles, the annual profit is between 6 to 72 US dollars which in their opinion was not sufficient incentive for EV owners want to participate in such a programme. However, in the same year, Peterson et al. also published their findings on the degradation of lithium-ion battery due to realistic driving pattern and V2G utilisation. They quantified the loss of battery capacity as a function of driving usage as well as a function of the energy processed due to V2G application. From their results, they claim that a PHEV battery pack can be cycled through a very broad state of charge range without significantly decreasing its capacity.

This paper presents a cost and benefit analysis of three different V1G and V2G utilisation scenarios in the New Zealand context. In the first scenario, EV owners are assumed to be charging their electric vehicles at night to take advantage of the night tariff if applicable. As an extension to this scenario, the use of the relatively cheap energy stored in a battery to supply the household during daytime is also analysed. It is worth noting that the differential between the day and night tariffs may reduce as the load increases during the night tariff period; this is not considered in this paper. In the second scenario, the potential cost saving for a retailer providing a smart charging scheme is investigated. This scenario assumes that the charging of EV batteries is regulated when the spot price is higher than a predefined limit. The third scenario considers a V2G application where the EV owners can participate in the electricity market for energy arbitrage. The additional cost associated with battery degradation due to V2G utilisation is included as part of this case study.

2. Scenario 1: Night Tariff

This section presents an analysis of a passively controlled battery charging scenario where the electric vehicle (EV) owners are expected to only plug in their vehicles at night for charging during the period where a night tariff is offered by the retailer. Practically this could be implemented by way of the EV's inbuilt timer, such as that in the Nissan Leaf. This scenario makes the following assumptions,

1. The electric vehicle used for this analysis is a 2011 model of the Nissan Leaf,
2. The battery capacity is 24kWh,
3. The energy consumption is 0.212 kWh/km according to the United States Environmental Protection Agency [9],
4. The average daily commute distance in New Zealand between 2008 to 2010 according to the NZ Transport Agency is recorded in Table 1 [10].
5. The EV owner is assumed to be on a variable day and night tariff from Genesis Energy.
6. The inverter is 90% efficient.

From these assumptions, the annual saving by the EV owner from charging their batteries during the night as opposed to charging during the day can be calculated as

$$Saving(\$) = \Delta Tariff(\$/kWh) \times Distance(km) \times EnergyConsumption(kWh/km) \times 365 \quad (1)$$

where *ΔTariff* is the difference between the day and night tariff offered by the energy retailer (excludes GST and prompt payment discount). The calculated annual saving for six chosen cities across New Zealand are recorded in Table 2. The results show savings above $100 in the South Island as well as in Wellington. In particular, Christchurch and Dunedin reached savings above $300 and $200 respectively. This suggests that there could be a strong incentive for EV owners in Christchurch and Dunedin regions to change their charging habit in order to take advantage of the cheaper tariff.

Table 1: Commute Distance by Private Vehicle in New Zealand.

Year	Auckland (km)	Wellington (km)	Canterbury (km)	Average (km)
2008-2010	24.28	31.10	20.46	25.28

Table 2: Variable Day and Night Tariff Offered by Genesis Energy.

	Day Tariff (¢/kWh)	Night Tariff (¢/kWh)	Difference (¢/kWh)	Benefit ($)
Auckland	20.76	16.15	4.61	90.18
Hamilton	24.13	20.54	3.59	70.23
Wellington	20.34	11.66	8.68	169.80
Nelson	22.59	16.05	6.54	127.93
Christchurch	27.43	10.18	17.25	337.44
Dunedin	24.12	11.13	12.99	254.11
Average Price	23.23	14.29	8.94	174.88

As an extension and comparison to the above calculation, a homeowner could use the cheaper energy stored in a battery (not part of a vehicle) to power the house during the day when the cost of electricity is higher. However, under this scenario, the cost of the battery and the efficiency of the inverter must be taken into account when calculating the actual cost of energy supplied from the battery. Assuming the cost of a lithium-ion battery with three-thousand life cycles ranges from $500 to $1000 per kilowatt-hour and the efficiency of the power conversion is 90%, the battery usage cost can be calculated as

$$Cost(\$/kWh) = \frac{BatteryCost(\$/kWh) \times BatteryCapacity(kWh)}{BatteryLifeCycle \times BatteryCapacity(kWh) \times Efficiency} \quad (2)$$

From equation (2), it is clear that battery capacity does not contribute to the battery usage cost, and therefore the homeowner will choose a battery size based on the energy consumption of the house and its associated capital cost. In order for this to be economically feasible, the battery usage cost must be lower than the difference between day and night tariff (*ΔTariff*). The battery usage cost is calculated to be 18.52 and 37.04 cents per kilowatt-hour for a battery costing $500/kWh and $1000/kWh respectively, and the difference between *ΔTariff* and the calculated battery usage costs are summarised in Table 3. It is clear from the result that, at current battery prices, it is not economical to purchase a battery to supply a house. Worse, additional hardware such as an inverter is required and incurs extra capital cost.

Table 3: Battery Usage Cost

City	Difference between Day and Night Tariff (¢/kWh)	*ΔTariff* - Battery Usage Cost (¢/kWh)	
		Battery Capital Cost @ $500/kWh	Battery Capital Cost @ $1000/kWh
Auckland	4.61	-13.91	-32.43
Hamilton	3.59	-14.93	-33.45
Wellington	8.68	-9.84	-28.36
Nelson	6.54	-11.98	-30.5
Christchurch	17.25	-1.27	-19.79
Dunedin	12.99	-5.53	-24.05

3. Scenario 2: Regulated Charging

As opposed to a passively controlled charging scheme, this section presents a scenario with an active charging control which regulates the battery energy consumption when the spot price is above a predefined limit. This enables the purchase of energy when it is relatively cheap. The benefit of having such a scheme can be calculated by modelling the charging of battery and the use of the EV. This scenario makes the following assumptions,

1. The electric vehicle used for this analysis is the 2011 model of a Nissan Leaf,
2. The battery has a capacity of 24 kWh,
3. The battery charger initially starts at 14 kW and follows an exponential decay as suggested by the measurement data in [12], it is expected to fully charge the battery within an eight hour period,
4. The vehicle is taken off-grid during hours between 8 am and 6 pm for the purpose of commuting,
5. The battery is expected to lose 26% of its stored energy each day for commute assuming an average commute distance of 25.28 km and an energy consumption of 0.212 kWh/km as identified in the previous section,
6. The smart charger will ignore the charging threshold if the energy left in the battery is less than what is required for an average distance commute,
7. The inverter is 90% efficient,
8. 2013 spot price data was used.

Based on these assumptions, the annual cost to charge the electric vehicle at the spot price is summarised in Table 4; the benefit columns show the difference between the cost at a certain regulation threshold and the cost with no regulation threshold. The results show marginal benefits even when the battery charging threshold is set to a spot price of $50/MWh.

Table 4: Annual Cost of Regulated Charging at Spot Price.

	Annual Cost of Charging				
	Cost to charge with no regulation ($)	Cost to charge below $100/MWh ($)	Benefit to charge below $100/MWh ($)	Cost to charge below $50/MWh ($)	Benefit to charge below $50/MWh ($)
Auckland	85.97	72.67	13.3	54.56	31.41
Hamilton	85.30	72.17	13.13	54.77	30.53
Wellington	85.62	71.47	14.15	56.43	29.19
Nelson	82.09	67.42	14.67	60.61	21.48

Christchurch	79.62	65.80	13.82	59.34	20.28
Dunedin	75.21	62.56	12.65	57.77	17.44

4. Scenario 3: Energy Arbitrage

In this scenario, the EV owners are able to participate in the electricity market by trading the energy stored in the batteries. The smart charging control is to buy energy when the spot price is below a predefined threshold to charge the battery and sell energy back into the electricity market when the spot price is above a predefined threshold. The same assumptions are made as the previous sections but the cost of battery degradation is included in this analysis.

The battery degradation cost is calculated by modelling the battery state of charge through its commute and V2G utilisation. The change in state of charge is accumulated which determines the number of life cycles the battery has gone through. This is then translated to a battery degradation cost. However, the effect of temperature is not included in this analysis. The economic benefit varies with different combination of battery charging and discharging thresholds, and this is clearly illustrated in Fig. 2. The left corner of the surface usually represents the highest benefit combination of the thresholds because energy is bought at an extremely low spot price and then sold back to the market when the spot price is high. In addition, by doing so the amount of energy traded is minimised which in turn limits the cost of battery degradation. This can be confirmed by Fig. 3 where the lowest battery life cycle is also at the left corner of the surface while the highest peak occurs when the charging and discharging thresholds are extremely close i.e. the battery is always either charging or discharging and never at idle.

The results based on both 2012 and 2013 spot price data are presented in Table 5, and as a comparison Table 6 shows the result if the battery was not part of a vehicle based on the 2012 spot price data. The benefit made in the North Island cities are generally higher than the South Island cities due to higher spot price. In addition, more benefit was gained in the North Island during 2012 compared to 2013, and this is due to 2012 being a relatively dry year in both islands whereas in 2013 near record high annual rainfall was recorded in the South Island [13][14]. It is clear that it is hardly profitable for the EV owners to participate in energy arbitrage as the annual benefit is often less than ten dollars or even negative, this is due to the battery degradation cost associated with the additional use of battery. Furthermore, there is a capital cost associated with upgrading the household energy meter and the charging inverter to allow bi-directional power flow which is not included in this analysis. Thus there is no incentive for such a scheme unless the cost of battery is dramatically reduced. This result is consistent with the conclusion in [7].

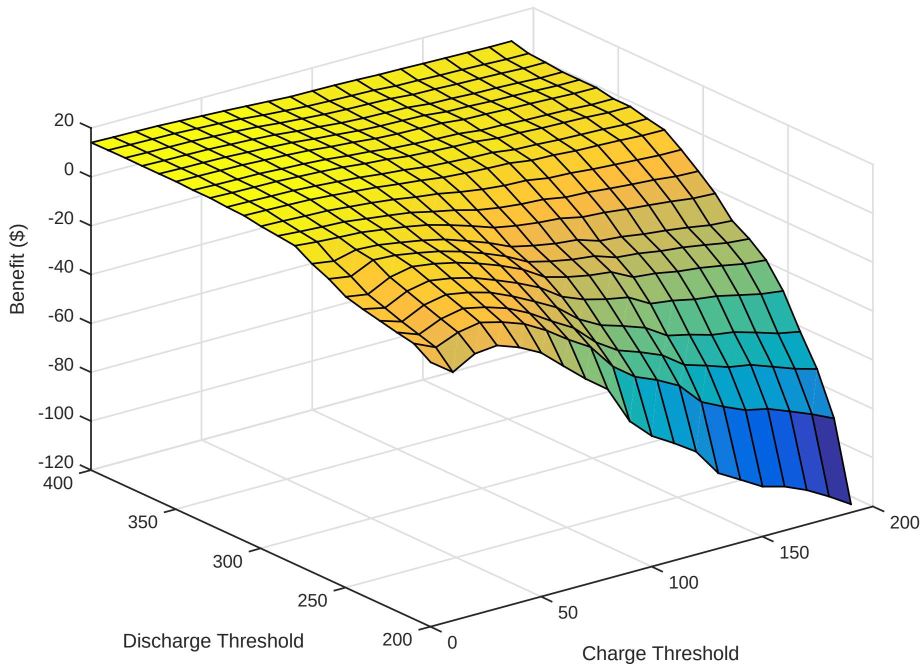

Figure 2: A typical surface of economical benefit resulting from energy arbitrage.

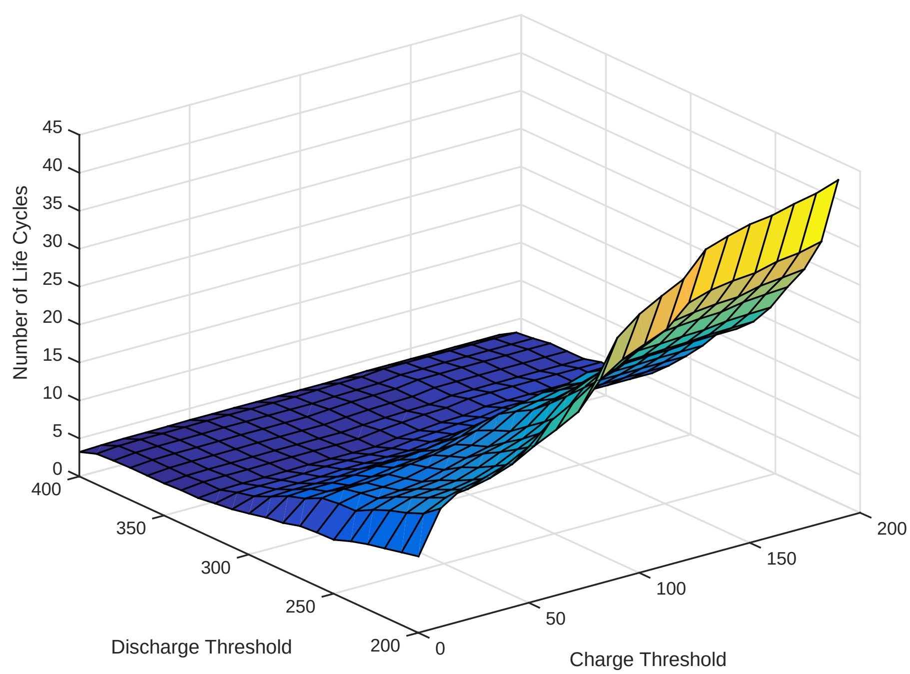

Figure 3: A typical battery life cycle surface resulting from energy arbitrage.

Table 5: The benefit of energy arbitrage based on 2012/2013 spot price data for commuting EV.

City	Benefit ($)				Battery Life Cycle due to Energy Arbitrage		Energy Traded (kWh)	
	Battery Capital Cost @ $500/kWh		Battery Capital Cost @ $1000/kWh					
Year	2012	2013	2012	2013	2012	2013	2012	2013
Auckland (PEN1101)	12.97	4.61	5.00	-4.47	1.99	2.27	96.15	109.55
Hamilton (HAM0331)	12.16	5.78	4.97	-3.61	1.80	2.35	86.78	113.28
Wellington (CPK0331)	13.89	4.03	3.06	-5.05	2.71	2.27	130.66	109.56
Nelson (STK0331)	1.78	4.26	-5.07	-5.86	1.71	2.53	82.70	122.12
Christchurch (ISL0331)	2.54	4.27	-4.32	-5.85	1.71	2.53	82.70	122.11
Dunedin (SDN0331)	2.89	3.79	-3.96	-5.83	1.71	2.41	82.64	116.09

Table 6: The benefit of energy arbitrage based on 2012 spot price data for standalone battery.

City	Benefit ($)		Battery Life Cycles due to Energy Arbitrage	Total Energy Traded (kWh)
	Battery Capital Cost @ $500/kWh	Battery Capital Cost @ $1000/kWh		
Auckland (PEN1101)	14.00	1.21	3.20	154.16
Hamilton (HAM0331)	13.04	1.79	2.81	135.53
Wellington (CPK0331)	14.64	-0.92	3.89	187.51
Nelson (STK0331)	1.79	-5.07	1.71	82.70
Christchurch (ISL0331)	2.29	-4.56	1.71	82.70
Dunedin (SDN0331)	3.10	-3.75	1.71	82.70

5. Discussion

Table 7 summarises the benefits of each case together to enable easy comparison between them. The results show that there is very little benefit for the EV owners participating in energy arbitrage (Case 3) due to the dominant battery degradation cost. It is by far more economical for EV owners to confine their battery charging pattern to the cheaper night tariff (Case 1). As for regulating the charging rate of batteries (Case 2), this is also less attractive to confining charging to the night tariff. However, there may be additional benefits available from allowing utility companies to regulate the charging of batteries, for ancillary services such as frequency keeping, instantaneous reserves, or even the dispatchable demand market. Both Case 2 and Case 3 assume that the electric vehicle is unavailable during the day, given the vehicle is used for commuting. However if charging infrastructure develops significantly, it may be possible to plug vehicles in during the day and thereby extend the period when vehicles are available to buy and sell energy. In turn this may make Cases 2 and 3 more attractive.

The analysis uses 2012 and 2013 spot market data, with 2012 being a dry year. For an exhaustive analysis other years should be examined and even scenarios that might occur in the future.

Table 7: Summary of annual benefits across different charging schemes.

	Benefit to charge on different tariff (Case 1, Section 2)	Benefit to charge below a certain spot price (Case 2, Section 3)		Benefit of energy arbitrage based on 2012/2013 spot prices (Case 3, Section 4)			
Regions	Night tariff ($)	< $100/MWh ($)	< $50/MWh ($)	2012 ($)	2013 ($)	2012 ($)	2013 ($)
Auckland	90.18	13.3	31.41	12.97	4.61	5.00	-4.47
Hamilton	70.23	13.13	30.53	12.16	5.78	4.97	-3.61
Wellington	169.80	14.15	29.19	13.89	4.03	3.06	-5.05
Nelson	127.93	14.67	21.48	1.78	4.26	-5.07	-5.86
Christchurch	337.44	13.82	20.28	2.54	4.27	-4.32	-5.85
Dunedin	254.11	12.65	17.44	2.89	3.79	-3.96	-5.83

6. CONCLUSIONS

Three scenarios of electric vehicles utilising V1G or V2G application have been presented in this paper. The passively controlled charging scheme, while relatively simple, is the most economically justifiable approach. The EV owners do not need to invest in any extra equipment to result in an average annual saving of $175. As for the regulated charging scenario, some benefit could be achieved but there is a cost for the utility companies to invest in a communication protocol in order to send control signals to the remote chargers. In the case of the third scenario where EV owners are participating in the electricity market for energy arbitrage, there is very little benefit associated with such a scheme and often results in losses due to the high battery degradation cost. This scheme is not economically feasible unless the cost of batteries decreases.

7. ACKNOWLEDGEMENT

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